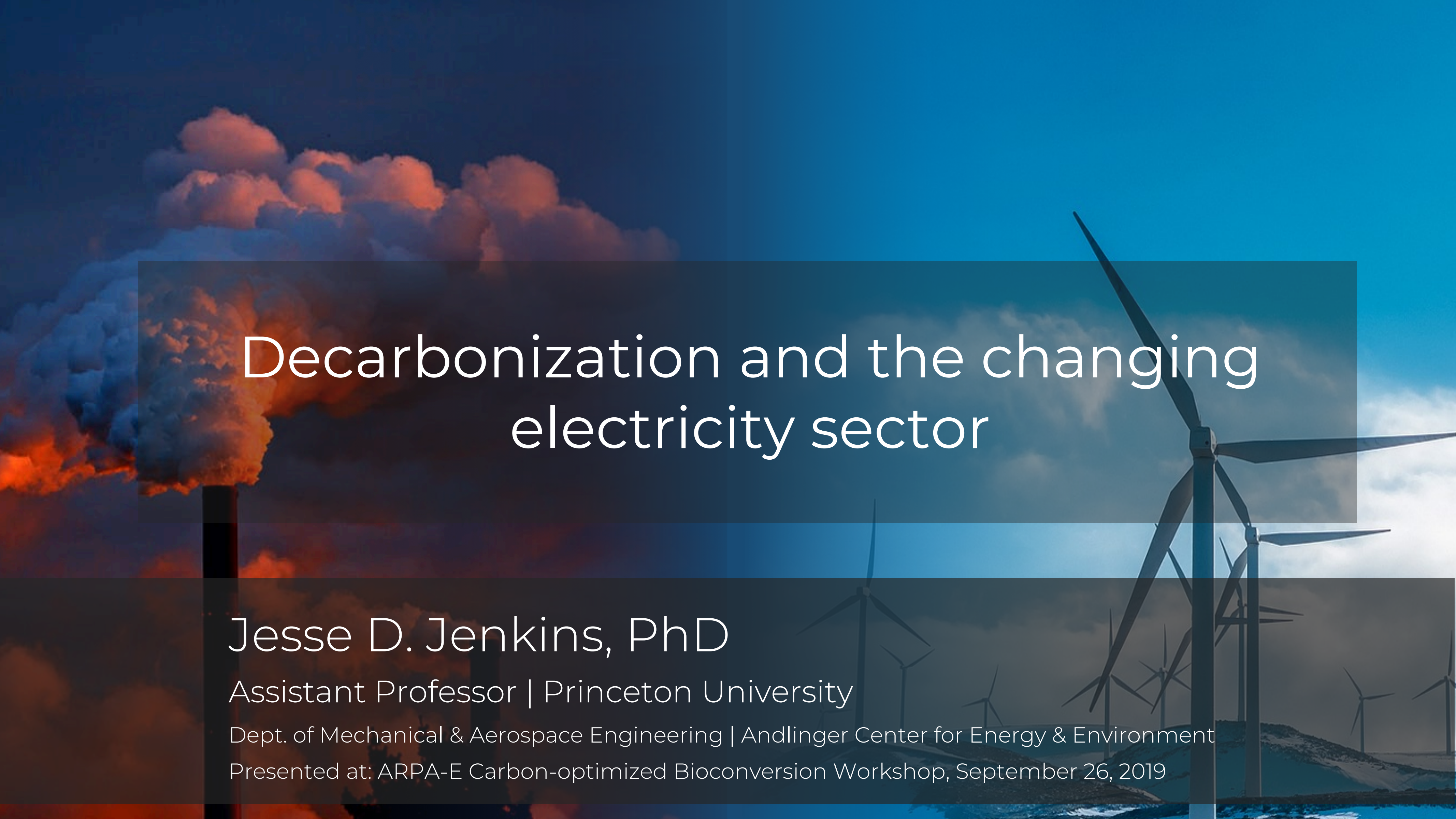

Decarbonization and the changing electricity sector

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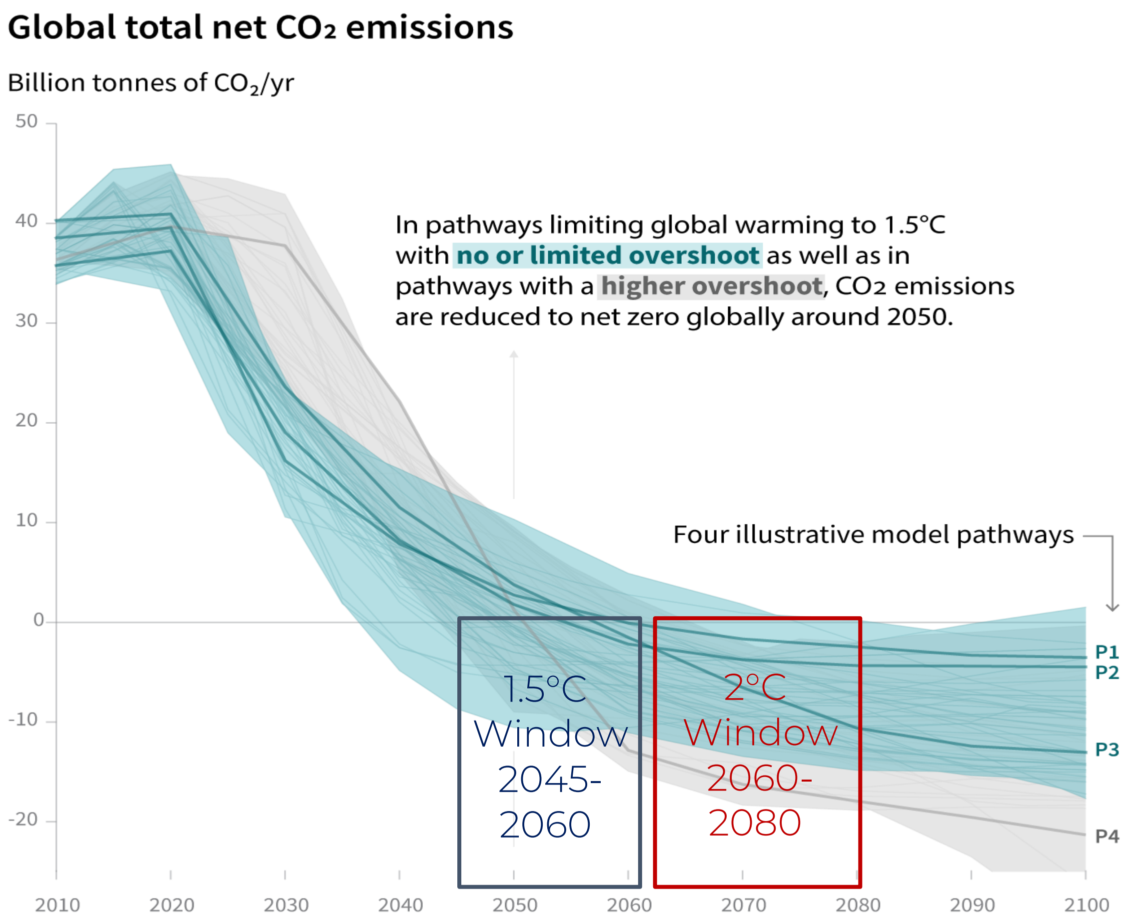
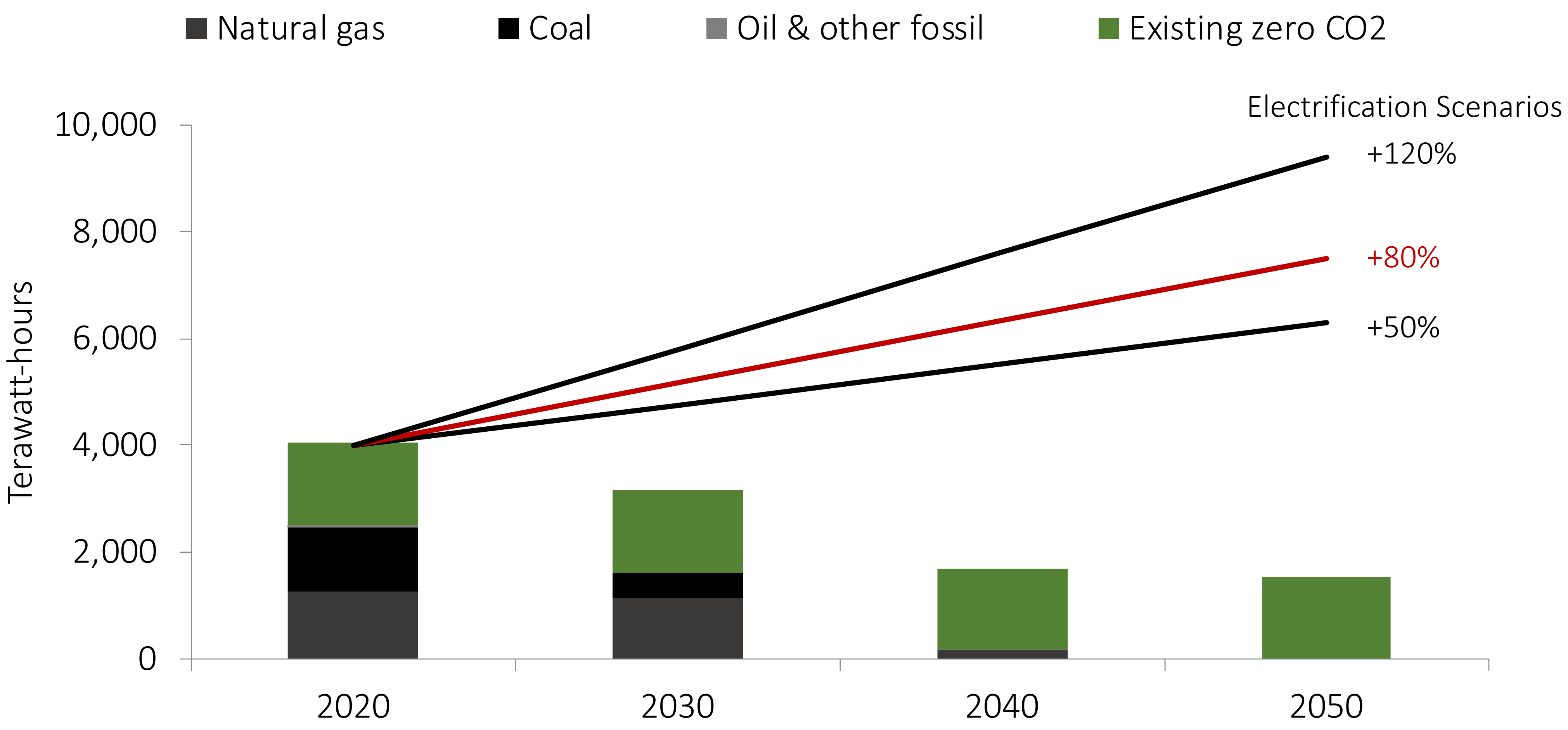
Dept. of Mechanical & Aerospace Engineering | Andlinger Center for Energy & Environment

Presented at: ARPA-E Carbon-optimized Bioconversion Workshop, September 26, 2019



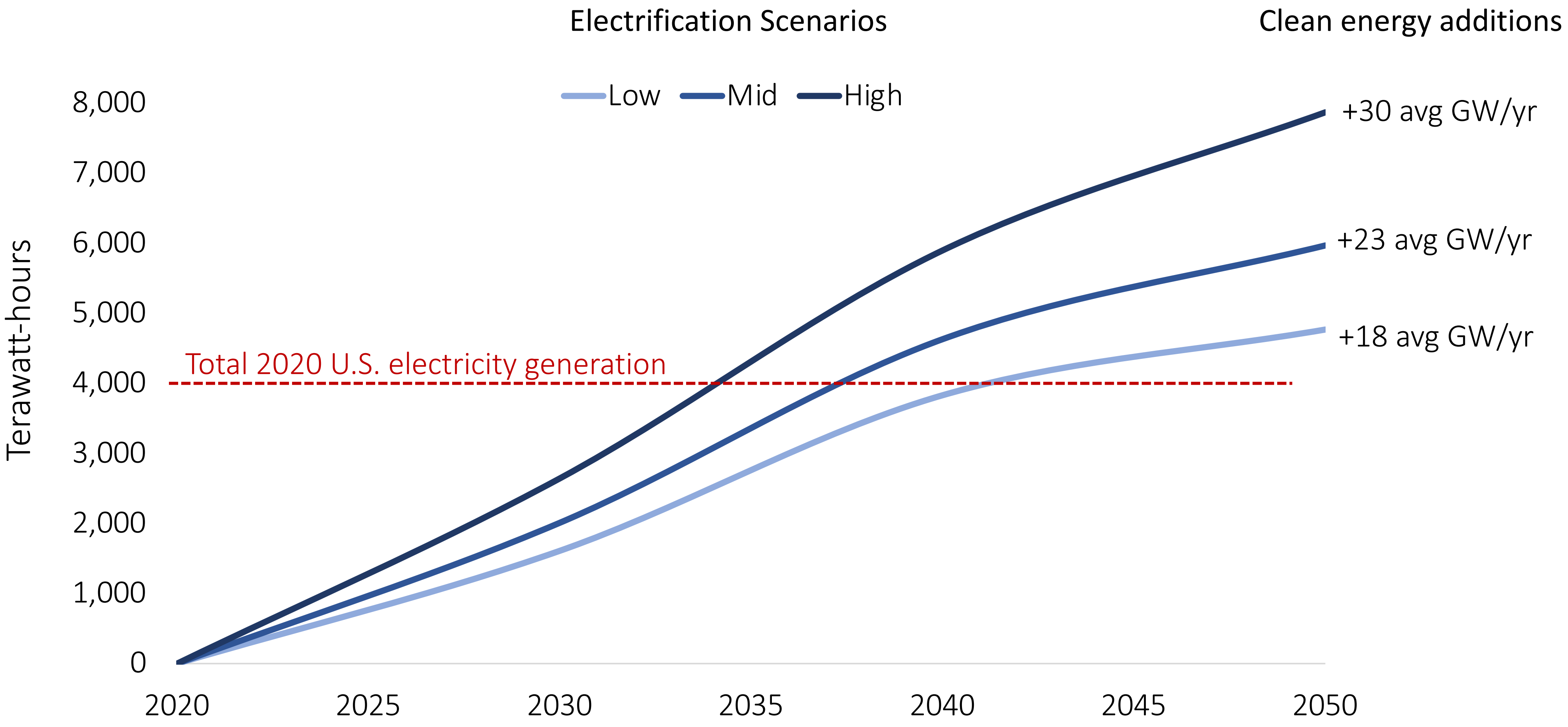
Source: IPCC (2018) Special Report on Global Warming 1.5°C

TWIN CHALLENGES FOR US ELECTRICITY: ZERO CARBON, 2X DEMAND



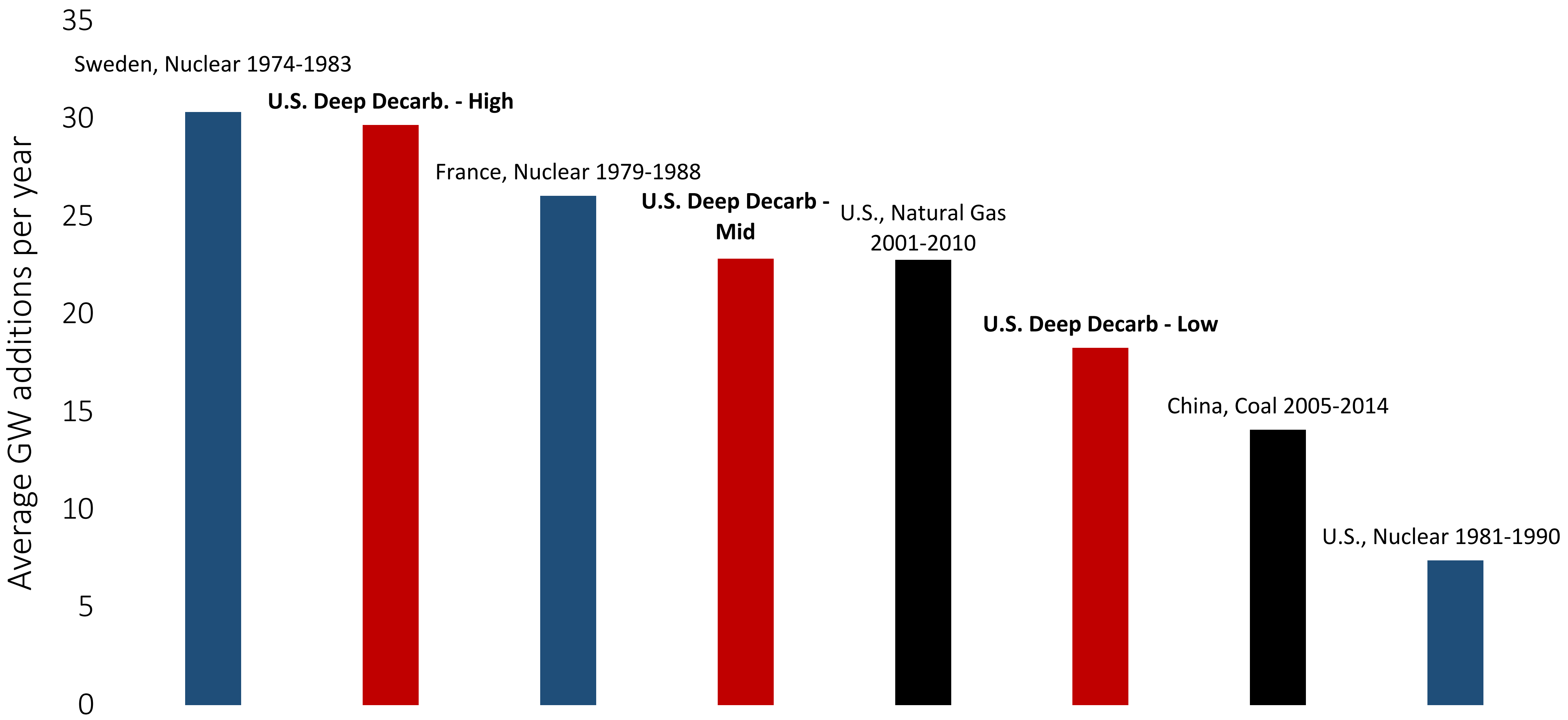
Data source: Iyer et al. 2017, GGCAM USA Analysis of U.S. Electric Power Sector Transitions (performed for the United States Mid-Century Strategy for Deep Decarbonization), Pacific Northwest National Laboratory; 2020 zero-carbon electricity supply from EIA Annual Energy Outlook 2019.

THE RAPID SWITCH: NEW ZERO CARBON ELECTRICITY NEEDED



Data source: Difference between projected electricity demand in Iyer et al. 2017 and 2020 zero-carbon electricity supply from EIA Annual Energy Outlook 2019. Assumes all 2020 generation can be sustained through 2050. Retirements of existing capacity would increase new zero-carbon generation needed.

HISTORICAL PRECEDENTS (SCALED TO U.S. POPULATION)



Data source: Historical per capita deployment rates from MIT 2018, The Future of Nuclear in a Carbon Constrained World, scaled to based on projected 2035 U.S. population of 364 million from U.S. Census Bureau.

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The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation

Nestor A. Sepulveda [4] • Jesse D. Jenkins • Fernando J. de Sisternes • Richard K. Lester •

Show footnotes

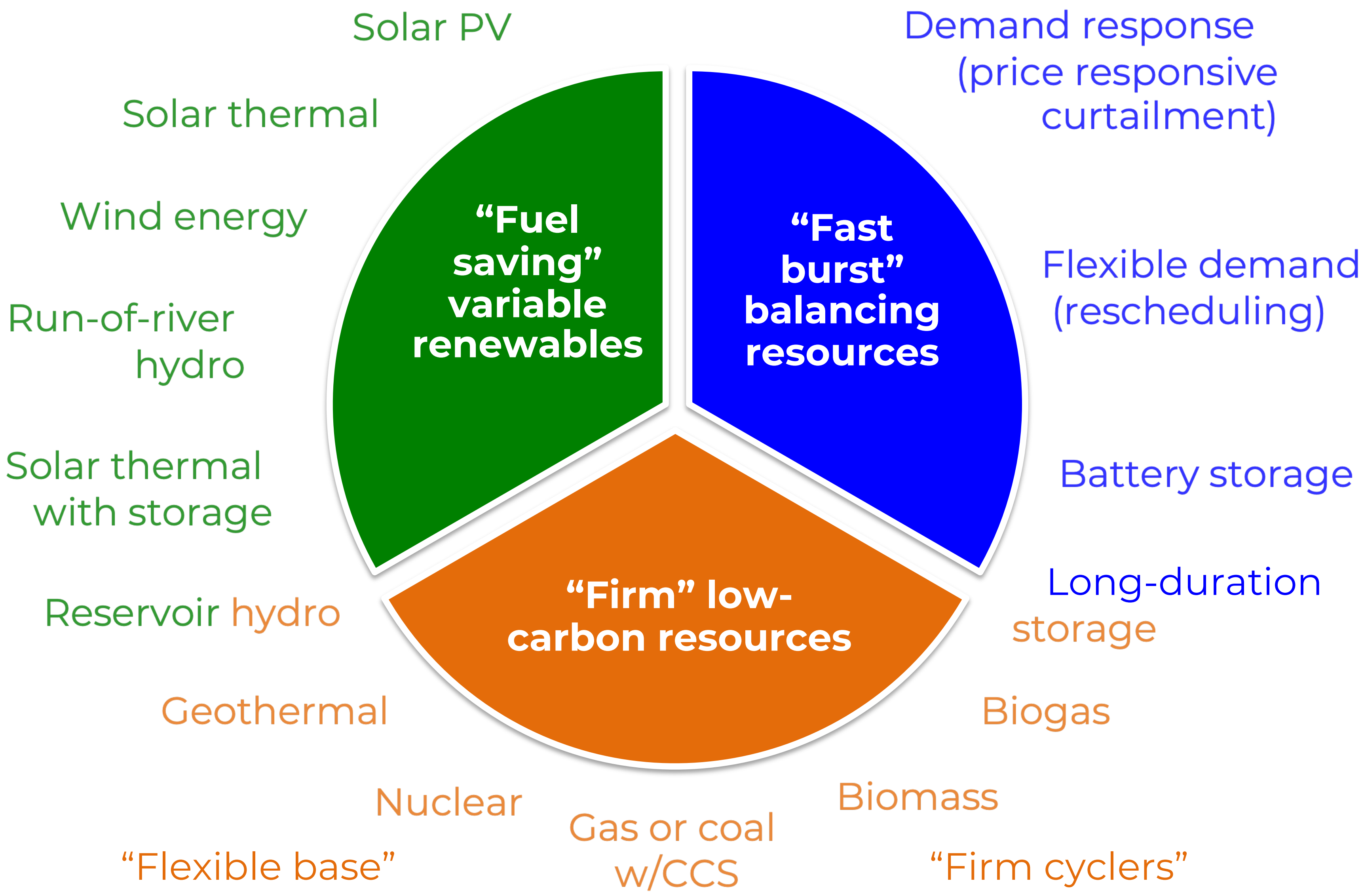
Published: September 06, 2018 • DOI: https://doi.org/10.1016/j.joule.2018.08.006

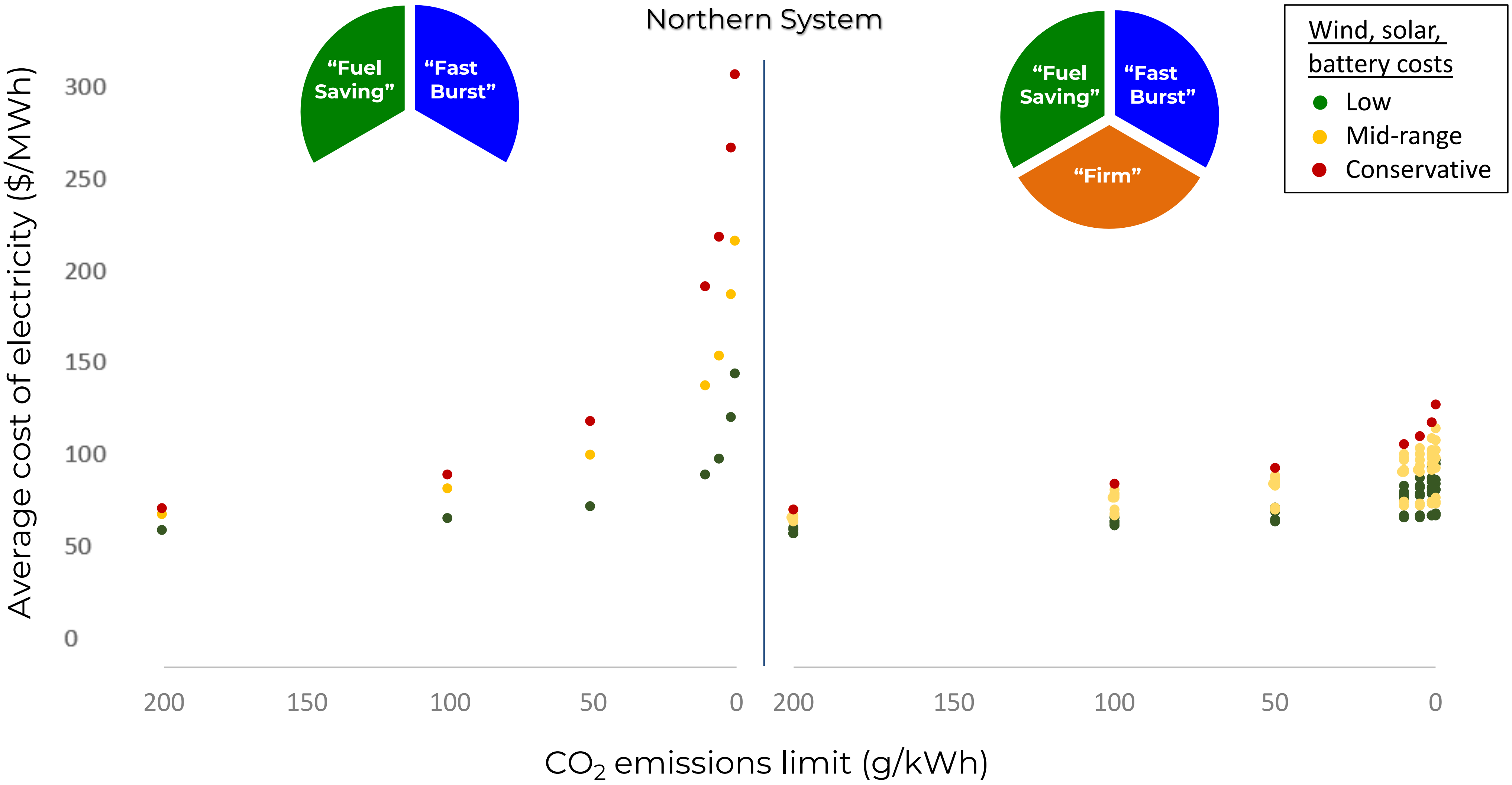
http://bit.ly/FirmLowCarbon

PlumX Metrics

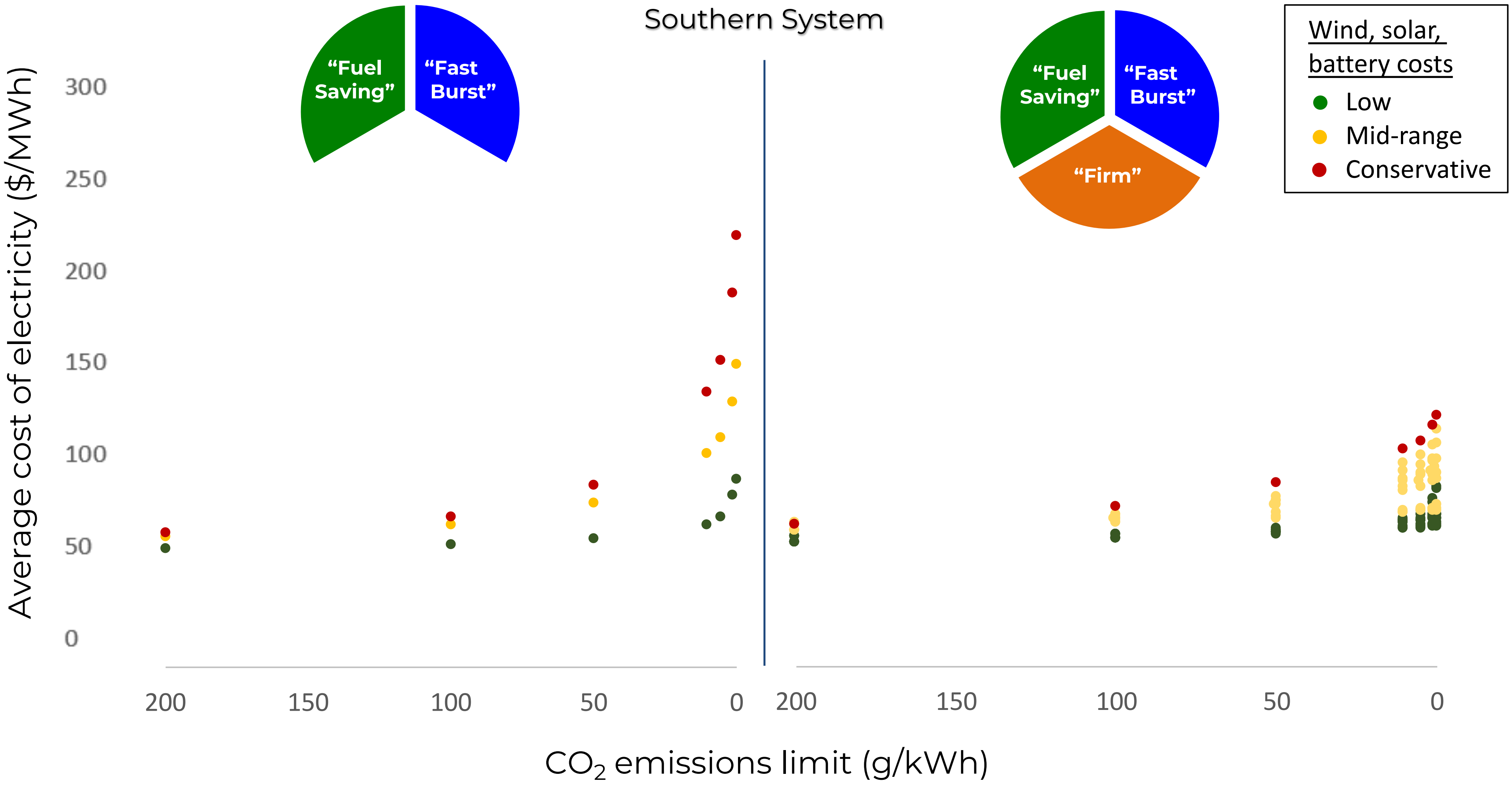
Highlights

- Firm low-carbon resources consistently lower decarbonized electricity system costs
- Availability of firm low-carbon resources reduces costs 10%–62% in zero-CO_2 cases
- Without these resources, electricity costs rise rapidly as CO_2 limits near zero


Solar PV
Solar thermal
Wind energy
Run-of-river hydro
Solar thermal with storage
Reservoir hydro
“Fuel saving” variable renewables
“Fast burst” balancing resources
Demand response (price responsive curtailment)
Flexible demand (rescheduling)
Battery storage
Long-duration storage
“Firm” low-carbon resources
Geothermal
Biogas
Nuclear
Gas or coal w/CCS
Biomass
“Flexible base”
“Firm cyclers”



Data source: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11).

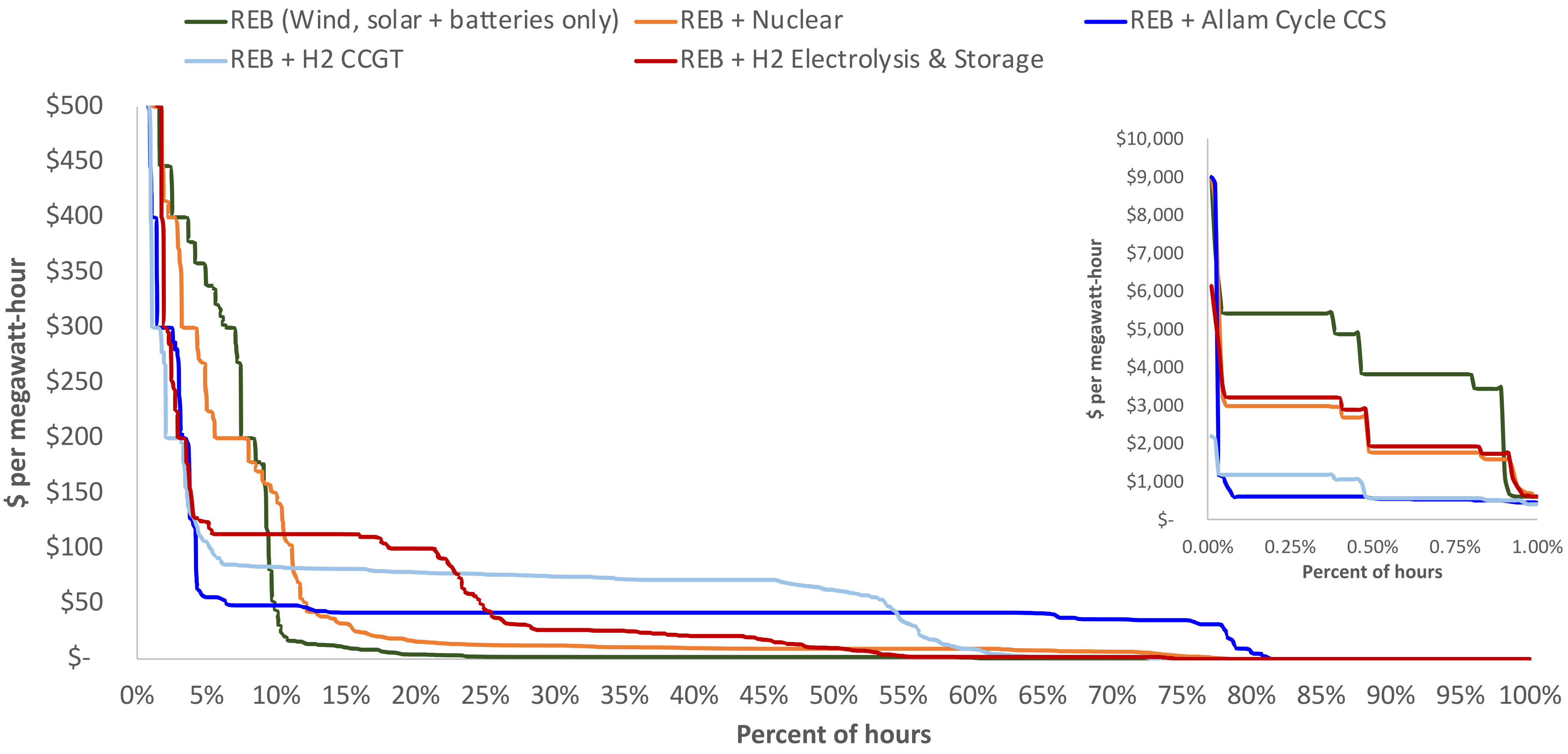


Data source: Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule* 2(11).

"The rapid deployment of renewable power such as wind and solar is **driving down both the cost and carbon intensity of electricity**, and is creating an opportunity to design new biorefining strategies that take advantage of low-carbon power to improve the efficiency of biomass conversion (e.g. accommodating external reducing equivalents made available from the strategic use low-carbon power)."

-ARPA-E Carbon-optimized Bioconversion Workshop announcement

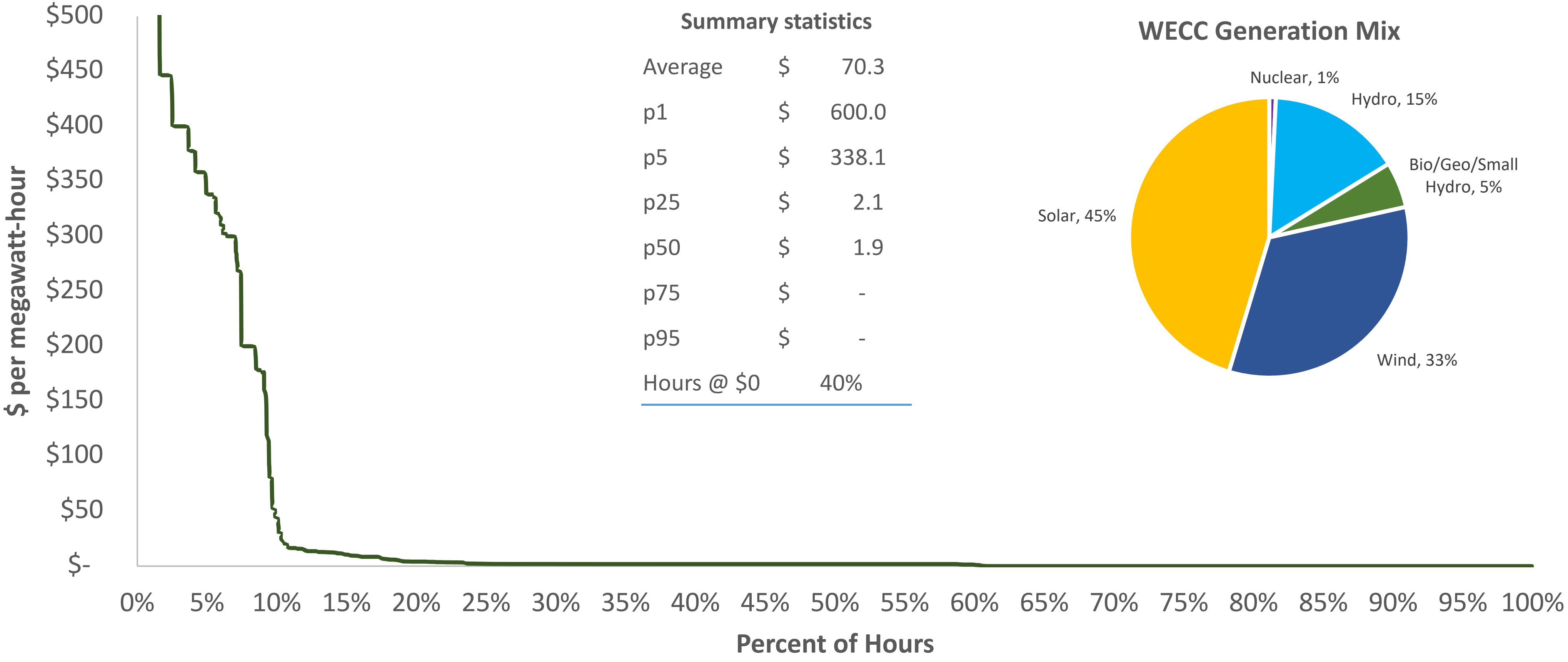
PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries Only



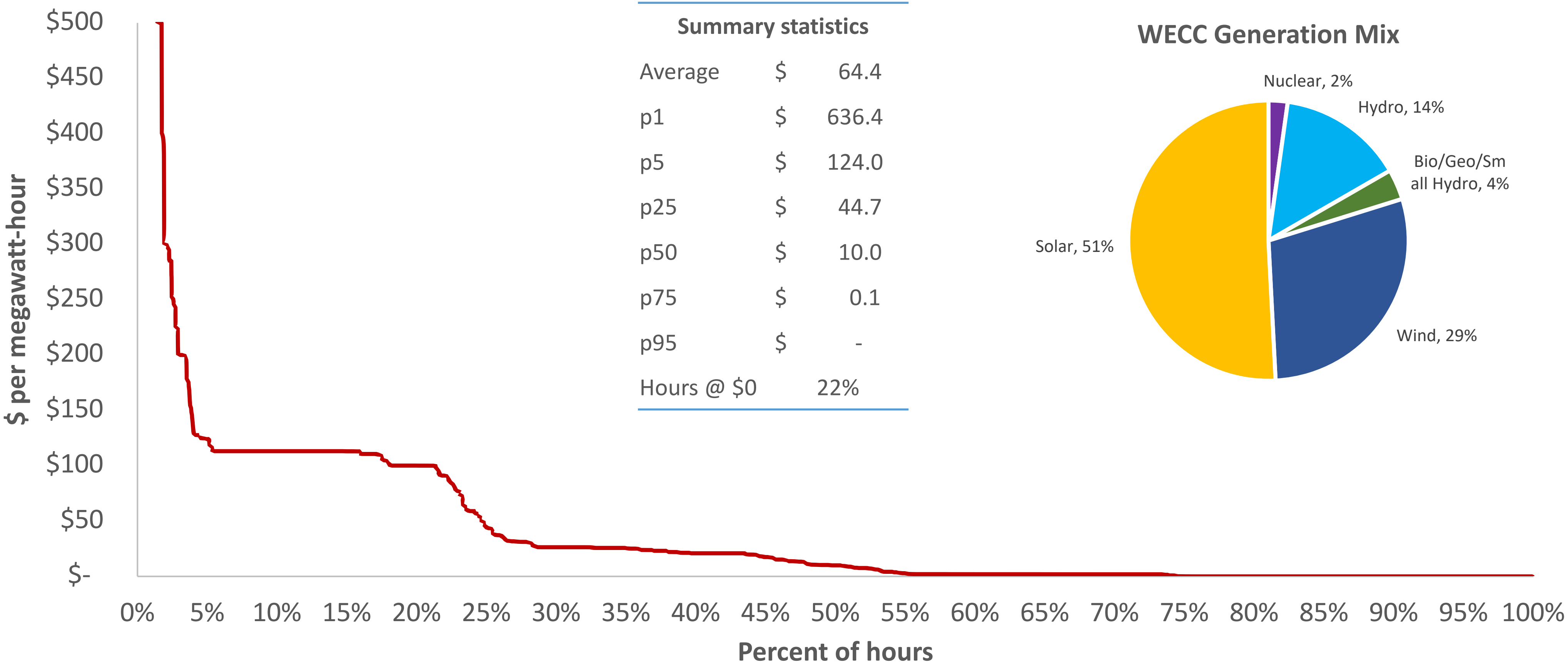
Summary statistics

Average	$	70.3
p1	$	600.0
p5	$	338.1
p25	$	2.1
p50	$	1.9
p75	$	-
p95	$	-
Hours @ $0	40%	

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + H2 Electrolysis w/Storage

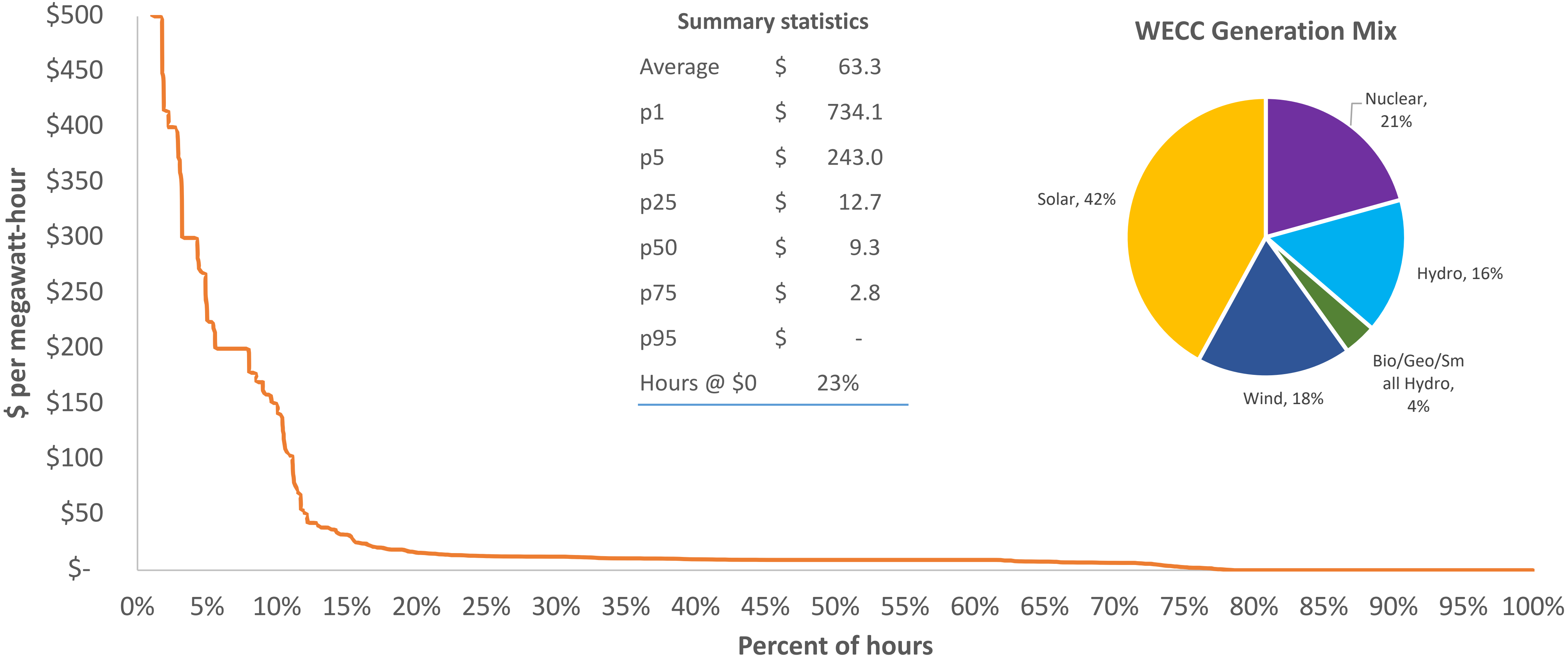


Summary statistics		
Average	$	64.4
p1	$	636.4
p5	$	124.0
p25	$	44.7
p50	$	10.0
p75	$	0.1
p95	$	-
Hours @ $0	22%	

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Nuclear

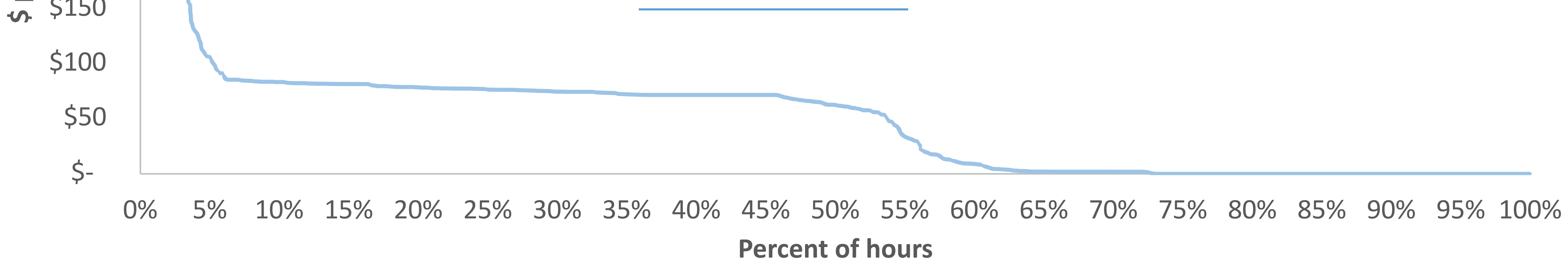


Summary statistics		
Average	$	63.3
p1	$	734.1
p5	$	243.0
p25	$	12.7
p50	$	9.3
p75	$	2.8
p95	$	-
Hours @ $0	23%	

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

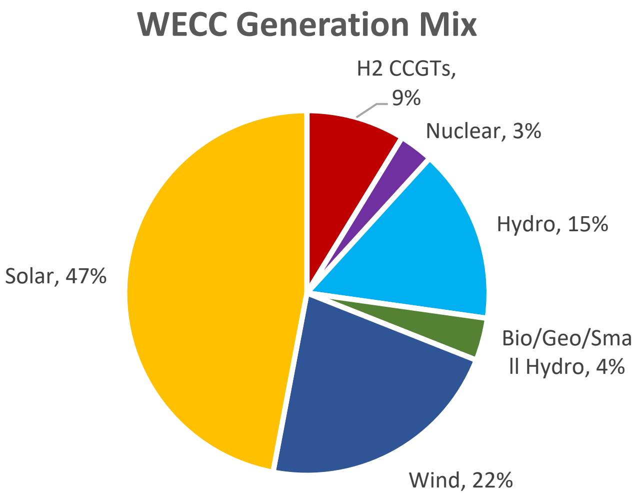
PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Hydrogen CCGTs



Summary statistics

Average	$	58.5
p1	$	455.0
p5	$	106.4
p25	$	76.5
p50	$	62.8
p75	$	-
p95	$	-
Hours @ $0	26%	

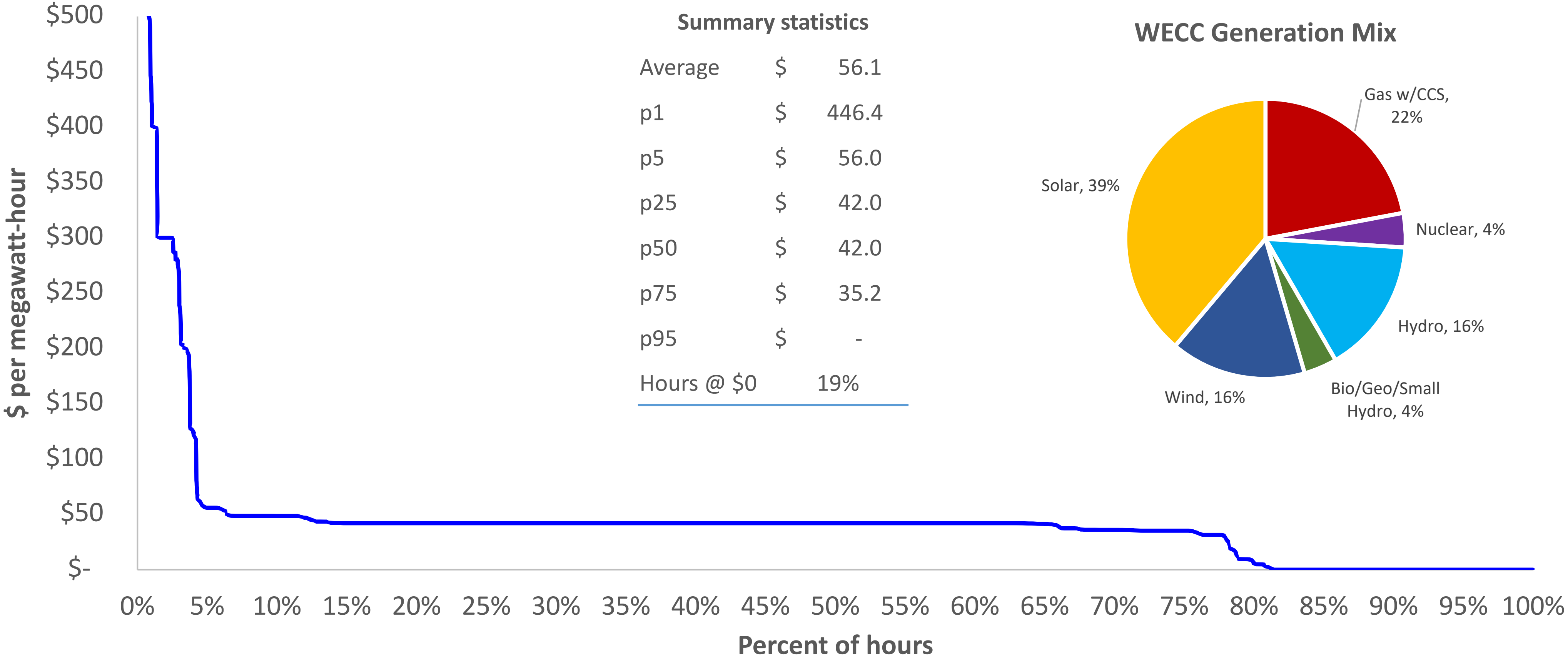


Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

PRICE DURATION CURVES – ZERO CARBON SYSTEMS, CA + WECC

Renewables + Batteries + Allam Cycle Natural Gas w/CCS

Summary statistics		
Average	$	56.1
p1	$	446.4
p5	$	56.0
p25	$	42.0
p50	$	42.0
p75	$	35.2
p95	$	-
Hours @ $0	19%	



Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

SUMMARY STATISTICS COMPARED

	REB	REB+H2 Electrol.	REB+Nuclear	REB+H2 CCGT	REB+Allam
Average	$ 70.3	$ 64.4	$ 63.3	$ 58.5	$ 56.1
p1	$ 600.0	$ 636.4	$ 734.1	$ 455.0	$ 446.4
p5	$ 338.1	$ 124.0	$ 243.0	$ 106.4	$ 56.0
p25	$ 2.1	$ 44.7	$ 12.7	$ 76.5	$ 42.0
p50	$ 1.9	$ 10.0	$ 9.3	$ 62.8	$ 42.0
p75	$ -	$ 0.1	$ 2.8	$ -	$ 35.2
p95	$ -	$ -	$ -	$ -	$ -
% hours <= $0	40%	22%	23%	26%	19%

Source: Unpublished modeling of zero carbon electricity systems in California and the Western Interconnection, Jesse Jenkins, Princeton University, May 28, 2019.

CLOSING THOUGHTS / QUESTIONS

- **Average** electricity prices do NOT fall in a zero-carbon electricity system (they likely increase)
- The **distribution** of prices changes significantly, especially if firm resources have low/zero marginal costs (nuclear, geothermal, hydro) or long-duration storage used to replace firm generation.
  - **Median** electricity prices fall in cases to <$2-10 per MWh
  - If H2 or natural gas combustion remains firm resource, **median** prices remain moderate ($42-63 per MWh)
- Number of hours of **zero price electricity** increases (approx. 20-40% of hours across scenarios)
- Can you **design bioconversion processes that operate flexibly** to take advantage of low-cost/free electricity inputs when available on a sporadic basis?
- If so, **how does a non-marginal increase in demand change price distribution?**

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